CHAPTER 19

Human Characteristics and Measures in Systems Design

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19.1 INTRODUCTION

The ebb and flow of ocean tides, the timing and exact placement of sunrise and sunset, seasonal fluctuations in weather with winter snows, tropical storms, seasonal monsoons, and migratory patterns of whales and many other creatures are natural events with cyclical and rhythmic characteristics. While these events may be difficult to describe with precision, they are quantifiable and predictable. We understand that such complex natural phenomena cannot be described using a single point in time or a single reference. The context and timing of the observation is critical, and a single measurement cannot accurately describe the complexity and dynamic nature of such a system. Similarly, the challenge posed by accurately describing human behavior requires understanding a vast array of conditions impossible to quantify with a few observations. Human behavior can seem mysterious, imprecise, overly complicated, and difficult to replicate. However, like other natural systems, human behavior is quantifiable and often predictable.

The human features prominently in the design of manned systems. However, engineering curricula do not typically address mental and physical characteristics of the human. Without this knowledge, design engineers do not have the tools to quantify the characteristics of the human and therefore often neglect the centrality of the human to systems design. Such human characteristics must be taken into account in the design, testing, and implementation of new technology and are central to human systems integration (HSI) (Booher, 1990).

There is room in the systems engineering design process to include all subsystems including the human component. The human subsystem, like other subsystems, has characteristics and predictable behaviors. Just as the design engineer selects the best materials based on their strengths and weaknesses relative to the design, design engineers

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must also design with the properties of the human in mind. For instance, one would not select reinforced concrete as the material for an aircraft skin. It has excellent structural properties but is too heavy for the application. Similarly, one would not purposely design a user interface that does not allow for optimal performance by the human nor design an interface that encourages the operator to make errors and perform slowly. Economic, time, and performance constraints often are the primary drivers in systems design. The HSI concept does not discourage the emphasis on these primary drivers. However, consideration of the human component is critical for most systems to meet realistic cost, schedule, and total system performance requirements.

19.1.1 Human System Characteristics

The characteristics of both human and nonhuman components of a system need to be thoroughly evaluated and understood if the benefits of the HSI approach are to be achieved. In an ideal situation, the requirements of the system will flawlessly match the characteristics of the human operator or maintainer, resulting in a one-to-one correspondence between task and person. Designing a system with the characteristics of the target audience in mind increases the likelihood of a superior product through enhanced system performance. Figure 19.1 illustrates such an integrated relationship.

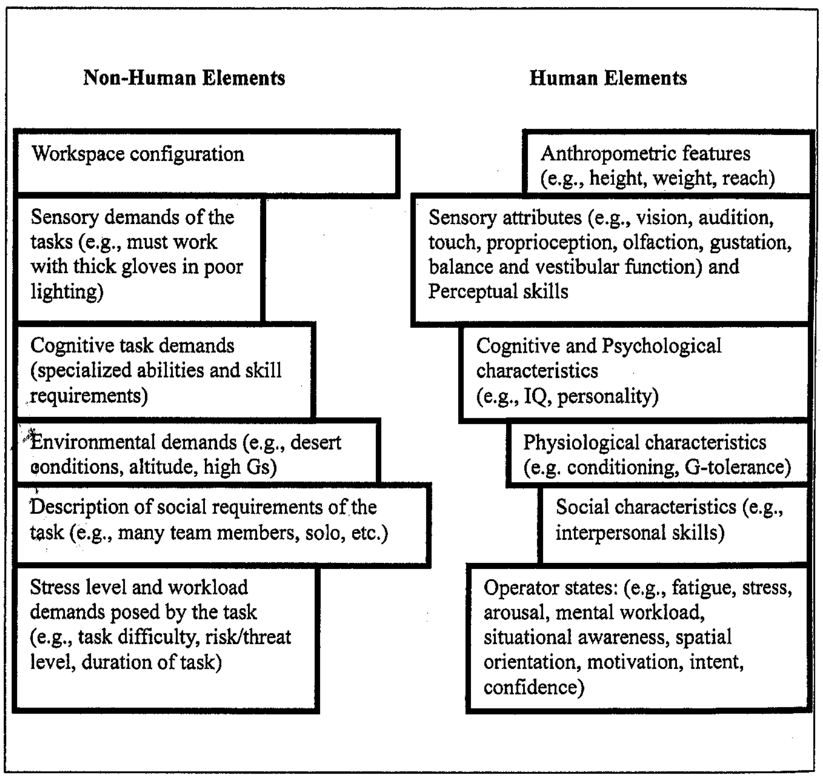

Figure 19.1 Total system with human and nonhuman elements.

The relationship seen in the two sides of the diagram is analogous to a lock-and-key mechanism, with both human and nonhuman sides having equally important and interdependent qualities. When the two sides map effectively onto each other, this relationship enables a smooth and dynamic boundary between the human and nonhuman components of the system. When the two sides do not mesh effectively, the person must adjust to the nonhuman components through increased personnel skill aptitudes, increased training, or by reduced performance. At best, this mismatch between human and nonhuman components causes additional and unnecessary workload; at worst, it increases the risk for accidents.

This chapter will focus on the right side of Figure 19.1 by describing those characteristics of people that help define them as system components.[1] The chapter will further introduce the reader to sources of information useful in deriving estimates of baseline limits and ranges in the capabilities of people. It will also explore how dynamic shifts in functional capability can occur from highly stressful and complex work environments. Situations that require high cognitive workloads, long work hours, or heightened levels of situation awareness (SA) can cause complete failures in total system performance if the human limitations have not been adequately designed into the system operational expectations.

19.1.2 Defining the Human Component of the System

Wherever possible in systems applications, it is important to work with measurable characteristics of the human. This chapter addresses many of the measures used to describe and accommodate the system user, operator, or maintainer. From an HSI standpoint, to adequately define the human component of the system, there must be an engineering understanding of the strengths and limitations of the population of users for which the system is designed. This description needs to define total system performance in such a way that the differences provided by the human component are measurable. Ultimately, knowing more about the human will allow the engineering design team to tailor the system for optimal performance, both from a total system perspective as well as from the perspective of the people who operate or maintain the system.

This chapter seeks to bridge an important gap between engineering and the behavioral sciences for HSI applications. We give an overview of characteristics, measures, and techniques that exist to quantify a variety of human factors categories including anthropometrics, sensation and perception, mental abilities, social abilities, physiological characteristics, and operator states under varying environmental conditions. Underlying this discussion of the primary human factor categories is the aim of recognizing, understanding, and accounting for the variance in human performance.

19.1.3 Chapter Overview

There are three primary questions that frame the chapter's discussion of the integration of the human into a system design:

1. How do we describe and measure human characteristics?
2. How do we consider limitations to human capabilities under varying operational states and adverse environments?
3. How do we integrate human components into the system being designed?

Each of these questions is discussed in the sections that follow by including information drawn from the literature and from applications familiar to the authors. A case study is presented in the last section to illustrate how the human considerations discussed can be applied to hypothetical but realistic systems.

19.2 HUMAN TRAITS: CHARACTERISTICS OF USERS

Each person has individual characteristics or *traits*, which combine in such a way that each person is unique, distinct from any other individual. People carry these characteristics with them wherever they go. Appreciating the inherent traits of each person is critically important for the systems designer who is creating a new system or modifying an existing system. The indwelling characteristics described in this section refer to traits or features of individuals that tend to remain constant over time. As shown in Table 19.1, these characteristics can be divided into five somewhat distinct categories:

TABLE 19.1 Human Factors Categories, Characteristics, and Measures

Categories	Characteristics	Measure/Technique
Anthropometrics and physical parameters of the body	Physical dimensions; range of motion (static and dynamic), strength	Anthropometry: Manual and automated methods Published norms and standards for specific populations
Sensation and perception	Vision, audition, proprioception, olfaction, gustation, balance, motion	Standardized techniques for sensory threshold testing, just noticeable difference (JND), static and dynamic measures
Cognition and psychological attributes	General intelligence, memory, cognitive style, problem-solving skills, and decision making ability	Standardized tests of intelligence, performance, cognitive style, problem solving and decision making
Social and personality factors	Personality traits and interactions with other humans; socialization	Measures of personality, social skills, and team performance
Physiological factors	Neuronal, electrophysiological, psychophysiological, biochemical, and hormonal	Electroencephalogram (EEG), Electromyogram (EMG), Electrodermal activity (EDA/EDR), electrocardiogram (ECG), heart rate, blood pressure, pupillary response, electrooculogram (EOG), plasma, and salivary cortisol and other hormone levels

1. Anthropometrics and physical parameters of the body
2. Human sensation and perception
3. Cognition and psychological attributes
4. Social and personality factors
5. Physiological factors

Table 19.1 gives an overview of factors that are frequently used to describe the human component of a system. The first column categorizes the factors, the middle column shows some of the human characteristics that fall into each category, and the last column of the table lists some of the measures and techniques that can be used to quantify those characteristics. In some systems design cases, an accurate representation of the target audience will require that one consider all of these characteristics for all categories, while in other cases, only a subset of one category might be necessary for an adequate description of the human component. For example, designing a military system requires different considerations for the human operators and maintainers (e.g., ease of human interface, reliability, and ease of maintainability) than when designing a similar system for a civilian system where life and death may not hinge on the quality of the human systems interface.

19.2.1 Anthropometrics and Physical Parameters of Body

The science of measurement of the human body is known as *anthropometry.* Anthropometry exists as a discipline because people vary considerably in height, weight, body mass, reach, and flexibility. This field encompasses physical and biomechanical traits or characteristics, as well as physical geometry, properties of mass, and human strength capabilities. Anthropometry is used in a wide range of applications, including industrial design, consumer product design, medicine, garment/clothing design, personnel selection, human factors and ergonomics, and office design (Roebuck, 1995). Human dimensions vary independently (e.g., a person with a long torso and short legs may be the same overall height as another person with a short torso and long legs).

Anthropometric measurements are traditionally divided into two areas: static and dynamic. *Static* measurements are passive, physical body dimensions (without motion). Static measurements are typically used to determine size and spacing requirements (e.g., height, weight, distance from elbow to extended finger tip, thigh circumference, or floor area required for a person seated at a desk). *Dynamic* measurements assess motion-related properties including reach, range of motion, endurance, force exertion, and physical strength. Both static and dynamic measurements are used to fit a user to a physical environment and to ensure that control locations are accessible.

An understanding of anthropometry and anthropometric methods is essential for systems design and for the operation of any type of machine, environment, or workplace that involves people. Because ergonomic design principles have been popularized in the mass media, today most designers and engineers know what anthropometry can offer and maintain an awareness and appreciation of how to use anthropometric data and measurements.

Anthropometry is population specific. It is important to identify who will use the system and to use anthropometric data appropriate to that group of users (McDaniel, 1998). These "normalized" databases have tended to focus on U.S. military users and

systems (Marras and Kim, 1993). If a commercial system is being designed, these data may not be appropriate; therefore, the design engineers have to become involved in "hands-on" anthropometric measurements. There are a number of population references available, but designers need to be mindful of the limitations of each data set. For example, many databases have been drawn from the U.S. military population, which is mostly white males and may not be applicable to civilian populations or minority groups and women. A few of these widely recognized data sets are:

1. Anthropometry Research Project Staff, *Anthropometric Source Book*, Vols. I, II, and III, 1978
2. *Ergonomic Design for People at Work*, Eastman Kodak Co. 1989
3. U.S. Department of Defense, *Military Handbook, Anthropometry of U.S. Military Personnel*, 1991

A more complete list of anthropometry databases and references is included in the Additional Readings section at the end of this chapter. The measurements reported in these sources are typically obtained using physical measurements of both static and dynamic dimension using a variety of traditional rulers, calipers, goniometers, and anthropometers. Some of these devices are pictured in Figure 19.2.

These tools have not changed markedly over the past 100+ years. Such techniques, still widely used and yielding valid data, are giving way to computer modeling. Computerized anthropometric modeling programs are capable of using traditional measurement data to build complex three-dimensional (3D) models of the human (Vannier and Robinette, 1995). These computer-generated models now allow multidimensional assessments and animations, including virtual reality scenes. There is one important caveat: Such programs are based on data obtained using the traditional mechanical devices, and the availability and expense of digital 3D data will be a limiting factor in their use for the foreseeable future.

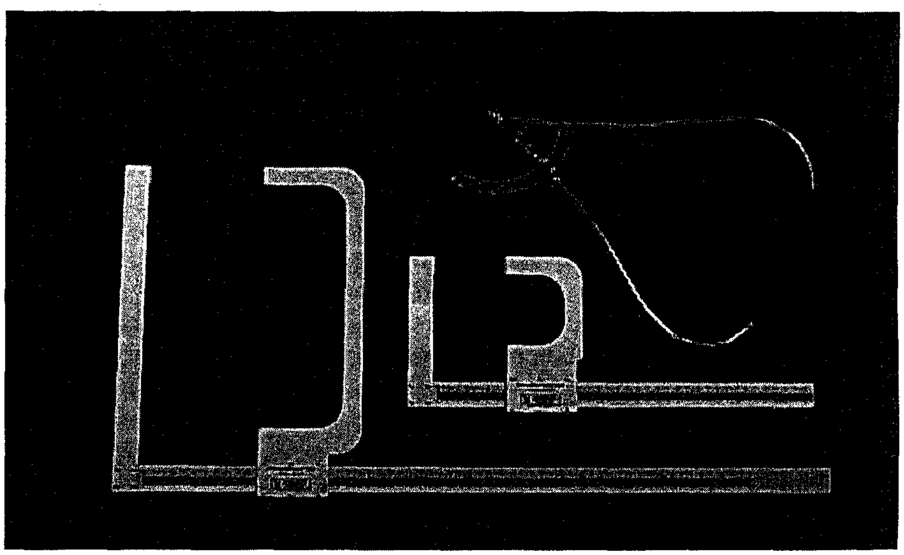

Figure 19.2 Anthropometric tools. (Courtesy of Lt. Paul Patillo.)

A recent development in anthropometric methods is laser scanning (Bhatia et al., 1994; Vannier and Robinette, 1995). This methodology is very accurate and useful for static measures but is expensive, time-consuming, and resource intensive. However, the use of laser scanning overcomes the issues of measurement accuracy and data entry and results in a more flexible 3D model of the human.

19.2.2 Human Sensation and Perception

Humans, like most organisms, have a suite of sensors whose primary responsibility is to glean information about the world. The eyes, ears, nose, tongue, skin, and other sensory organs feed information into the human cognitive and decision-making system. Of particular importance to HSI applications are sensory detection and recognition and the related higher order perceptual functions such as depth perception, auditory localization, and motion perception. These sensory domains include the electromagnetic spectra for vision and audition, and particulate detection in olfaction and gustation. The touch senses, including touch, proprioception, and haptic senses, all are designed to detect pressure. A threshold is the minimal amount of stimulation necessary for a human to detect a particular stimulus (light, sound, taste, odor, pressure, etc.; Ludel, 1978).

The scientific discipline of psychophysics examines the relationship between physical properties of the environment and the detection of those properties by a human (Gescheider, 1997). Signal detection theory is an essential tenet of psychophysics, predicting for each sense and for each situation under investigation when and how people will be able to detect a faint or weak signal against background clutter or noise (Parasuraman et al., 2000; Wickens, 2002). There are no absolute thresholds, and like other sensor systems, response varies with respect to the environment and the individual human being. The ability to detect a weak stimulus (a "signal") is a function of signal strength but is heavily influenced by operator trait and state (e.g., motivation, fatigue, stress, expectations, etc.). Both Boff and Kaufman (1986) and Salvendy (1997) are excellent resources for more detailed information on sensation and other human factors topics.

Perception and Response Bias Each individual has a unique ability to perceive sensory stimuli, and this perception is critical to the resultant responses made by an individual following a sensory stimulus. Responses can often differ radically between people exposed to the same stimuli. Perception varies as a function of many factors and can lead to differences in perception between individuals, providing one type of *response bias*. Issues such as expectancy, fatigue, and stress may contribute to such response bias in an individual. In July of 1988, a tragic example of this type of response bias was seen in the USS *Vincennes* incident in which a passenger airliner was incorrectly identified as a hostile aircraft. The crew mistakenly fired on the airliner, resulting in many civilian casualties (House of Representatives Committee on Armed Services, 1992).

Vision The human visual system is a complex system that provides us with information regarding form, color, brightness, and motion. Approximately 80 percent of all information processed by humans is via the visual system. This system, typically conceptualized as an extension of the brain, conveys light energy via chemical, neural, and higher order mental and cognitive processes to the visual centers of the brain for integration, evaluation, and interpretation.

The pupil is the variable opening in the iris, which allows differing amounts of light to enter the eye as light waves, which pass through the flexible lens (which is used to maintain focus). The light waves are focused on the retina, forming an inverted image on the rods and cones. Neural impulses from the retina are then transmitted via the optic nerve to the brain and create a corresponding pattern of nerve impulses in the brain, thereby triggering a series of neural impulses in the brain's visual center. Typical measures of human visual function include measures of visual acuity (both near and distance), contrast sensitivity (both static and dynamic), stereopsis, and tests of color vision. Measuring a person's vision at a single point in time fails to take into account the predictable visual changes that occur with aging. For those seeking further information, excellent treatments of the visual system may be found in Barlow and Mollon (1982), Goldstein (2001), or Regan (2000). Table 19.2 presents a description of the visual system and important design considerations.

Audition The human auditory system is the second most important source of information for most individuals. It consists of (1) the ear and associated neuroanatomy, (2) a source of sound, and (3) a transmission medium. The eardrum receives external sounds and transfers them via the middle ear bones to the oval window of the cochlea. The motion is transmitted via fluid-filled canals in the cochlea, which stimulates the cilia within the canals. These cilia, when activated, transmit neuronal impulses via the auditory nerve to the auditory centers of the brain. Sound is typically referred to as both the physical sound that enters the ear and our response to that sound. Hearing is typically used to refer to our subjective response of the auditory system to the sound. This distinction is necessary because our perception of sound does not have an exact linear relationship to the physical sound that enters the ear canal. Sound results from vibrations emanating from a source,

TABLE 19.2 Human Visual System Parameters and Design Considerations

Human Visual System	Parameters	Design Considerations
Rods (black, white, and gray only) > 0.01 lumens per ft^2 *Cones* (color) < 0.001 lumens per ft^2 *Minimum visible light intensity*: 1/1,000,000,000 of a lambert ftL *Wavelength of visible light*: 397–723 nm Violet, 397–424 nm Blue, 424–491 nm Green, 491–575 nm Yellow, 575–585 nm Orange, 585–647 nm Red, 647–723 nm	• Visual acuity • Visual field • Depth perception • Motion perception • Feature detectors (lines, curves, circles, etc.) • Color discrimination • Dark adaptation • Absolute threshold • Difference threshold • Flicker-fusion threshold • Stereoscopic vision • Single & double images • Apparent motion • Optical illusions • After-images • Accommodation • Saccadic eye movements	• Light levels (illumination) • Coding • Pattern recognition • Motion detection • 2D/3D convergence • Dim-out (lighting) conditions • Glare/shadows • Diffused light • Direct/indirect light • Aesthetics of color • Transillumination (of control panels) • Color coding

and emits pressure fluctuations in all directions at a speed that depends on the transmission medium (air, water, etc.). The vibrations are cyclic and consist of frequency, intensity (pressure level), and duration. An excellent source for information on these theories is found in Barlow and Mollon (1982) and Buser and Imbert (1990). Table 19.3 presents a description of the auditory system and important design considerations.

Haptic Sense: Touch Nerve endings in the skin and surrounding tissues transmit information regarding our immediate environment. These neurons or nerve cells are specially adapted to transmit information from specialized receptors for pain, pressure, cold, and heat. Specific neural receptors in the skin appear to respond to each of these. The sense of touch helps in our perception of form and is an important source of information for tactile information that is received from knobs and control surface textures. Table 19.4 presents a description of the haptic system and important design considerations.

Vestibular Through the otolith and the semicircular canals, the vestibular senses contribute to our sense of stability and give us cues for determining our orientation, self-motion and balance. Normally, the visual system is the dominant sense but it is closely coupled, even hard-wired, to the vestibular system. *Vestibular opportunism* occurs in the absence of visual cues when vestibular inputs must be resolved without their concomitant visual inputs (e.g., a pilot flying in the clouds loses visual references and may become disoriented by trusting a false perception provided by the vestibular system). Motion sickness and the related syndrome of simulator sickness occur when sufficient low-frequency alternating acceleration is transferred to the vertical (z) axis of the body and/or when there is a mismatch between visual, vestibular, and other sensory cues (McCauley and Sharkey, 1992). This cue mismatch or sensory decoupling causes malaise and nausea (Harm, 2002; Flaherty, 1998). In the absence of visual cues, this vestibular opportunism

TABLE 19.3 Human Auditory System Parameters and Design Considerations

Human Auditory System	Parameters	Design Considerations
Frequencies between: 20 and 20,000 cycles per second. *Minimum intensity*: 5 cycles per second (≈ 15 dB) (For most people) *Maximum intensity*: 100,000 cycles per second (≈ 140 dB) (pain threshold for most people) *Gender* Men: Better at hearing low-frequency tones Women: Better at hearing high-frequency tones *Loudness* [just noticeable difference (JND)]: < 20 dB $=$ 2–6 dB JND > 20 dB $= \frac{1}{2}$–1 dB JND	• Frequency • Intensity • Voice recognition • Auditory masking • Auditory fatigue • Vocal intelligibility • Individual differences • Age-related decrements • Gender effects • "White" noise	• Pattern recognition • Tones vs. speech • Signal vs. noise • Intelligibility • Speech distortion • Sound localization • Extraneous noise impact on performance

TABLE 19.4 Haptic Sensory System Parameters and Design Considerations

Haptic System: The Sense of Touch	Parameters	Design Considerations
Skin senses 1. *Pain:* *Mechanical, chemical, thermal, electrical:* Varies with location on body and pain type: (e.g., thermal: 0.21 gram-calories per second per cm^2) 2. *Pressure:* Inward/outward on skin Vibration: Pressure sensitivity 3. *Cold:* 4. *Heat:* Skin is a poor conductor of heat and cold. It is possible to achieve partial or complete adaptation to thermal conditions.	• Reflexes • Reaction time • Muscle tremor • Repetitive movements • Fine vs. gross motor movements • Skin sensitivity	• Tactile feedback
Pain range: 0.02 (cornea) to 300 (fingertip) g/mm^2 *Pressure range:* 2.0 (tip of tongue) to 250 (sole of foot) (g/mm^2) *Neuron* (nerve): Electric potential takes between 300 to 1000+ msec to fire (refractory period limits the frequency with which a neuron may fire). **Muscle, Tendon and Ligament Neural Receptors** *Muscle Tissue:* Low efficiency (three fourths of energy released as heat; only one fourth in useful work)		

can result in vestibular illusions or spatial disorientation. Vestibular issues for design consideration arise in moving platforms and in stabililized platforms with peripheral visual cues where decoupling of the two senses may occur (Stoffregen et al., 2002; Hettinger et al., 1990). A description of the vestibular system and design considerations are presented in Table 19.5.

Gustation and Olfaction The chemical senses of taste and smell, while important to us from the standpoint of enjoying our daily lives, have experienced limited applicability for human factors engineers and HSI professionals. Exceptions to this rule are the use of an olfactory warning for detection of leaking gas, and the experimental use of wintergreen mint to alert drowsy drivers. Table 19.6 discusses the olfactory and gustatory sensory systems and lists potential design considerations.

19.2.3 Cognition and Psychological Attributes

This section addresses mental ability such as intelligence and cognitive processes such as memory function and decision making. All of these human characteristics are interde-

TABLE 19.5 Vestibular System Parameters and Design Considerations

Vestibular System: Sense of Balance and Self Motion	Parameters	Design Considerations
Vestibular system: Gives position and movement of the head Three Semicircular canals: orthogonal to sense angular acceleration Two Otolith Organs: linear accelerometers to indicate head position and orientation *Kinesthesis*: Body awareness in 3D space + joints; muscle contractions; Kinesthetic fibers are large = rapid conduction of information	• Acceleration/ deceleration • Motion sickness • Sopite syndrome • Vestibulo-Ocular Response	• Relationship to other senses (especially vision)

pendent and interrelated. To maximize overall system effectiveness, these characteristics in the design population should be assessed and considered in systems design.

Intelligence Quotient The cognitive capability of humans, particularly the ability to process information, is known as *intelligence* and is more commonly referred to as an *intelligence quotient*, or *IQ*. In humans, intelligence is not just a process or capacity but is regarded as the intellectual capabilities of one person relative to some standardized population. Psychologists have developed a number of standardized tests to assess individual intelligence and capability for learning (Kaufman, 2000; Snell, 1996). Typically, an IQ score in the range of 70 to 135 is considered to be within the "normal" range. Scores below 70 indicate that the individual may have difficulty functioning in society, while a score over 135 indicates that the individual has exceptional abilities and may function at an intellectually higher level than most other people. While systems designers will probably never administer an IQ test, it is important to consider the intelligence level of the human

TABLE 19.6 Olfactory and Gustatory Senses and Design Considerations

Senses of Taste (Gustation) and Smell (Olfaction)	Design Considerations
Taste: Gustatory neurons: Proximity receptors (must be stimulated by direct contact) Tongue has areas for detecting *bitter* (most sensitive: Can detect 0.0005 percent solution), *sweet*, *sour*, and *salty* *Smell:* Olfactory neurons: Direct extensions of the brain. Smell involves mechanical and chemical stimulation (e.g., ammonia = smell + pain receptors) Ethyl alcohol: 0.2 of a milligram per liter Vanilla: 1/1,000,000 of a milligram per liter	• Limited design considerations for smell at this time (use of noxious odor in natural gas and wintergreen for drowsy drivers) • No known design considerations for taste at this time

who will be using and maintaining the system, especially when designing a complex and cognitively demanding system. Systems designers must work closely with personnel selection professionals to ensure that the system being designed is appropriate for the design population.

Cognition Cognition is the exploration of how the human mind processes information, what incoming information it processes, and what it does with that information after it is processed. There are a number of theories about how the brain deals with information, but they are beyond the scope of this chapter. Suffice it to say that there are some widely accepted characteristics of human information processing that are useful, even critical, to the system designer. Again, it is important to work with human factors professionals in an iterative design process to ensure a usable product for the target population. Cognition occurs at the interface between perception and memory. Perception is used to bring information into the system for processing. Memory is used to retain perceived information while determining which to use now, which information to use later, and which to throw out. Bringing information in from external sources is the function of perception; holding on to information while deciding what to do with it is the function of memory.

Memory, Decision Making, and Cognitive Style These three characteristics refer to the way people process, store, and act on information from the environment. *Memory* has a number of characteristics, including limitations on the amount of information that can be held at one time and restrictions in retention and recall of that information. *Decision making* results from the processing of information from the outside world. *Cognitive style*, or the characteristics of the user's response, is vitally important to overall outcome and is essential for the achievement of optimal system performance. For example, one operator may be extremely methodical—slow to respond and careful to avoid errors—while another might respond quickly and impulsively with little regard for errors. Table 19.7 indicates several important design considerations relevant to these three cognitive processing topics.

19.2.4 Social and Personality Factors

Individuals have unique social characteristics and needs. Our socialization process begins at birth and continues through the school years into adulthood. In this respect, it can be stated that social skills are not static but are continually undergoing adjustment and development. These individual social skills can have a tremendous impact on an individual's effectiveness and ability to work as a team member and should be considered both in workplace design and in personnel selection. The social environment and physical proximity of individuals in the workplace configuration and the impact of personality within a social system are vitally important considerations for the systems design team. It is understood that people perform better when their personal space and personal needs are taken into consideration. Submariners, for example, need to be selected partially based on their ability to work well in confined spaces and in close proximity to other crew members.

Personality Personality can be thought of as a distinctive pattern of *relatively enduring* behaviors, thoughts, and emotional responses that define who we are and how we interact with other individuals in our environment. Our personalities are generally flexible enough

TABLE 19.7 Cognitive Characteristics Design Considerations

	Design Consideration
Memory Characteristics	
Attention	Humans have a limited attention span. They are particularly bad at vigilance tasks requiring sustained attention or monitoring. Humans perform poorly on tasks that are boring.
Chunking	Humans can learn to group information together in ways that allow them to remember more information. This includes grouping by likeness, location, or association. Most people can hold about 7 ± 2 items in memory at one time.
Heuristics/mnemonics	Heuristics are "rules of thumb" that facilitate recall. Mnemonic devices are mental tricks that allow humans to retain more things in memory than would otherwise be possible.
Forgetting	Regardless of how frequently things occur, people forget things. Forgetting can lead to errors or unacceptable performance.
Decision-making Characteristics	
Uncertainty	Uncertainty requires more cognitive work and places higher demands on memory. The display of information should support a reduction of uncertainty, resulting in faster and more accurate solutions.
Choice	As the number of choices increases, the cognitive and memory demands also increase exponentially. In a given operational scenario, display of information should reduce the number of choices to the fewest number possible.
Cognitive Style	
Speed	The "speed/accuracy trade-off" is a hallmark principle of cognition with the two tasks being inversely related. Speed on a task will vary according to the instructions given to the operator. Speed is exchanged for accuracy with higher speeds related to less accurate performance.
Accuracy	The human operator will emphasize either speed or accuracy. The decision about which to emphasize should be made in the concept exploration phase of the system design.
Choice	The more choices the user must make, the longer the response will take. This is an opportunity for decision aids to support the selection of a response by providing supporting information or by limiting the number of choices available.
Errors	Errors occur. Unfortunately, many errors occur due to suboptimal system design. The effect of errors in each phase of the mission must be evaluated. "Fatal errors" result in redesign of the system, and it is better to identify them in the concept exploration phase than during production.

to allow us to adapt to a wide range of situations and to the behaviors of those around us. Human factors professionals and design engineers should remain aware of the effects of individual personality on the work environment and on the social environment at work (Holtzman, 2002).

19.2.5 Physiological Factors

Human physiology is based on the concept of *homeostasis*, the natural feedback system that continually strives to maintain balance in all cellular processes. Each of us possesses genetic determinants for our individual physiological makeup. These physiological traits include homeostatic functions such as metabolism and immune response. Physiological functions can be measured and quantified using a wide variety of techniques such as the electrical activity of the brain, heart, and skin; pulse and respiratory rates; and biochemical indicators such as hormone levels collected in plasma, salivary, and urine samples. These physiological traits are affected by the various environmental and work conditions to which humans are exposed and as such will fluctuate from baseline levels when exposed to conditions such as fatigue and arousal.

19.3 HUMAN STATES: OPERATIONAL AND ENVIRONMENTAL VARIATIONS

This section focuses on the importance of *transitory human states* and the effects these states have on system performance. Covering the depth and breadth of all human operator states is well beyond the scope of a single chapter. However, as examples, the following states and their effects on system performance are discussed: mental workload, fatigue and circadian rhythms, psychological and physiological stress, and SA.

Various techniques including physiological measures, measures of performance (MOPs), and measures of effectiveness (MOEs) are described as they relate to monitoring the state of the human in the system. Table 19.8 lists transitory human operator states and candidate measurement techniques for quantifying these states.

19.3.1 Mental Workload

Most systems require some level of mental work by the operator or user. Whether setting the clock on a DVD player or cooking food in a microwave, users perform mental work. To

TABLE 19.8 Transitory Human Operator States and Candidate Measurement Techniques

Operator States	Candidate Measurement Techniques
Mental workload	Primary and secondary performance measures, subjective workload scales, physiological measures (e.g., EEG, oculography, cardiovascular measures, and respiratory rates)
Circadian rhythms and fatigue	Actigraphy, temperature, melatonin levels in saliva or plasma samples
Psychological and physiological stress	Physiological measures such as cortisol levels in saliva, plasma, and urine samples, psychophysiological measures (e.g., EEG, EDA, ECG, and EMG), subjective rating scales (both standardized and task-specific), SME-administered interviews
Situational awareness	Standardized ratings of SA, subjective questionnaires, SME ratings of SA

determine the mental workload required by a system, it is necessary first to have a definition of workload. One definition of mental workload is that it is "the amount of cognitive or attentional resources being expended at a given point in time" (Charlton and O'Brien, 2002, p. 98).

Cognitive psychologists and human factors professionals have used a variety of strategies in their attempts to measure mental workload of the human. The intuitive approach to measuring mental workload is to simply query the operator. However, by interrupting the user during the task, the observer has intruded upon and altered the workload being measured. This alteration is referred to as *assessment reactivity*, and the results of such a measurement procedure may be prone to subjective bias. Conversely, assessing workload after the task is completed is also unsatisfactory because one ends up with an overall workload measure for the task but no data regarding workload during the task itself. Certain time segments of a task may be considerably more challenging and could therefore be expected to produce a higher workload. The single measure collected at the end of a task would fail to capture these fluctuations. Further complications are posed by innate individual differences in "workload capacity" [i.e., what is very hard for one person may seem less hard for another (Reid and Nygren, 1988)].

Until the "Vulcan mind-meld" (*Star Trek*, Paramount Pictures, 1970) has been perfected, what is needed is an unobtrusive and noninvasive "window into the brain." In this section, we will examine how mental workload has been measured in the past, how we are currently measuring it, and possible directions for future measurements of mental workload. Traditionally, mental workload has been measured in four ways:

1. Performance on primary task measures
2. Performance on secondary task measures
3. Subjective measures
4. Electrophysiological and psychophysiological measures

The first two methods, both performance measures, rely heavily on information processing models of attention that assume that performance will degrade with increasing workload. For years, theorists have been debating the details of information processing and attentional capacity models, and this debate continues (Charlton and O'Brien, 2002).

Performance Measures of Mental Workload When using primary task measures of performance to evaluate operator workload, operators are given tasks to complete. One task is identified as being relatively more important in the face of other competing tasks. Speed and accuracy of performance on that task is stressed. Operator workload level is derived from performance on that primary task. Using this metric, slower and less accurate performance suggests higher mental workload.

In the secondary task method, performance on the task not identified as important (the task that "suffers" when the operator becomes busy) is considered to be reflective of workload. Poor performance on the secondary task suggests that the workload level is too demanding. Examples of secondary tasks include time estimation, tracking tasks, memory tasks, mental arithmetic, and reaction time. In general, trying to "embed" secondary tasks into a primary task situation is difficult and may result in an artificial and intrusive measure. A comprehensive overview of both primary and secondary task measures, with their strengths and limitations, is found in *Human Performance Measures Handbook*

(Gawron, 2000). This handbook also gives excellent descriptions of a wide variety of human performance measures.

There are problems in using performance as a measure of workload. O'Donnell and Eggemeier (1986) cite four major areas of difficulty: (1) artificially enhanced performance with task underload, (2) a "floor effect" with task overload, (3) the operator's information processing strategy, training, or experience may confound the estimates of mental workload, and (4) issues with generalizing the results to other tasks. Additionally, a single measure of primary task performance may be overly simplistic, especially when the task is complex and multidimensional (Meshkati et al., 1990).

Subjective Measures of Mental Workload Subjective measures of mental workload have high face validity and are possibly the most intuitive and easiest to obtain. Gawron (2000) lists 34 separate subjective rating scales. Some scales are generic measures of workload, while others are designed for specific task domains such as estimating workload in an aviation cockpit.[2]

On the negative side, O'Donnell and Eggemeier (1986) offer these caveats for those using subjective ratings of workload.

- Mental and physical workload can be potentially confounded.
- It is difficult to distinguish the task difficulty from actual workload.
- Subjects cannot accurately rate their level of unconscious or preattentive processing.
- There is a dissociation of subjective ratings and task performance.
- Subjective measures require a well-defined question.
- Subjective ratings are highly dependent on the short-term memory of the rater.

Physiological Measures of Workload In contrast to performance and subjective measures of workload, physiological measures are relatively objective and unbiased. However, these measures, while inherently attractive, may be costly and unwieldy in field settings. In operational settings, psychophysiological measures have been used effectively to monitor the functional state of the operator, to determine the response of the operator to new equipment and/or new procedures, and to determine workload and vigilance levels of the operator (Wilson and Eggemeier, 1991). Wilson (2002, p.128) states, ". . . an operator's interaction with a system influences their physiology. By monitoring their physiology, we are able to infer the cognitive and emotional demands that the job places on the person."

Central to any discussion of physiological measures is the role of the nervous system in controlling all behavior, including both physical movement and cognitive processes. The nervous system relays information through the "firing" of electrical impulses, which propagates from nerve to nerve. The human nervous system can be divided into the central nervous system, or CNS, comprised of the brain and spinal cord, and the peripheral nervous system, or PNS, which comprises the cranial nerves and all other nerves. Activity from the CNS and the corresponding changes in cellular metabolic function can be monitored using a variety of methods. Table 19.9 describes some of the more important characteristics of these measurements of CNS activity.

TABLE 19.9 Central Nervous System Physiological Measures

Acronym	Name	Transducer Type	Where Conducted?	Expense	Ease of use
EEG	Electroencephalogram	Scalp electrodes	Field/lab	$	*
ERP	Event-related potentials	Scalp electrodes	Lab	$$	†
MEG	Magnetoencephalogram	Magnetic sensors	Lab	$$$	‡
fMRI	Functional magnetic resonance imaging	Magnetic sensors	Lab	$$$	‡
PET	Positron emission tomography	Radioactive isotopes and special sensors	Lab/hospital	$$$$	‡

$ = *Inexpensive*
$$ = *Somewhat expensive*
$$$ = *Expensive*
$$$$ = *Very expensive*
* = *Minimal training required*
† = *Specialized training required*
‡ = *Highly specialized technical training required*

At the level of the CNS, representative measures include:

- Electroencephalogram (EEG)
- Event-related potentials (ERP)
- Magnetoencephalogram (MEG)
- Functional magnetic resonance imaging (fMRI)
- Positron emission tomography (PET)

The last four of these measures require that the subject or operator remain relatively stationary. These measures also have serious operational restrictions posed by the cumbersome and nonportable nature of the apparatus required to record the signals (Center for Position Emission Tomography, 2002). However, recent advances in the EEG recording technology have resulted in portable, human-mounted devices that allow for data collection to be made real-time in field settings.

These five measures of central nervous system activity are not the only indications of nervous system activity, however. There are signals that can be observed peripherally to the brain that are also extremely good indicators of nervous system activity. Quite often, these peripheral measures are less invasive and more useful for field applications. Table 19.10 describes some of the more critical features of these peripheral measures.

At the level of the PNS, representative electrophysiological measures include:

- Electromyogram (EMG)
- Electordermal response (EDR)
- Cardiovascular responses (ECG, heart rate, and heart rate variability; blood pressure, echocardiogram)
- Respiratory rate
- Oculometry (EOG, or electroculogram, pupillary dilation, eye blink rate, and eyelid closure rates)

TABLE 19.10 Representative Peripheral Measures of Central Nervous System

Acronym	Name	Recording Transducer	Where Conducted?	Expense	Ease of Use
EMG	Electromyogram	Electrode over muscle	Field/lab	$	*
EDA/EDR	Electrodermal activity and response	Skin conductance electrode	Field/lab	$	*
EKG/ECG	Electrocardiogram	ECG electrodes	Field/lab	$	*
HR, HRV	Heart rate and heart rate variability	ECG electrodes	Field/lab	$	*
BP	Blood pressure	Sphygmomanometer	Lab	$	
RR	Respiratory rate	Spirometer	Field/lab	$	†
EOG	Electrooculogram, blink rate, eyelid closure rate	EOG electrodes placed beside eyes; camera	Field/lab	$	†
SV	Saccadic velocity	Eye reflectance and camera	Lab	$$	†
PD	Pupillary dilation	Eye reflectance and camera	Lab	$	†

$ = Inexpensive
$$ = Somewhat expensive
** = Minimal training required*
† = Specialized training required

Studies have shown that psychophysiological measures have the potential to precede or predict performance decrements (Cacioppo, 2000; Lewis et al., 1988). One remarkable feature of psychophysiological measures is the sensitivity at which they detect alterations and variations in human response. Many studies have demonstrated the utility of these peripheral measures in discriminating between workload levels (Wilson, 2002; Miller and Rokicki, 1996; McCarthy, 1996; Burns et al., 1991). Prodromal indicators of performance decrements would have great usefulness when assessing operator state and workload. One example of an operational military system that is using psychophysiological measures is the use of in-flight EEGs to detect G-induced loss of consciousness in Israeli Air Force pilots. Real-time monitoring of operator state has left the realm of science fiction and has become a reality. Recent advancements in the field of laser Doppler vibrometry hold promise for monitoring many human physiological signals.[3]

19.3.2 Circadian Rhythms and Fatigue

Human beings operate on an approximate 24-hour biological clock with a predictable pattern in many parameters of our behavior. For individuals who are adjusted to sleeping nights and working days, many physiological systems slow down in the very early morning hours as can be seen in the predictable drops in body temperature, heart rate, and blood pressure. Although the "normal" human body temperature is 98.6°F, body temperature is just one of many physiological parameters that varies with time of day and with the body

cooling off over the course of the night, reaching the coolest point in the early morning hours just before awakening and then beginning to warm up once again. Temperatures reach their peak at about 9:00 p.m. and then repeat this cosinelike cycle. Human performance also changes over the course of a 24-hour period. Performance on many tasks such as reaction time and vigilance mirrors the circadian variations seen in body temperature and other physiological indices (Krueger, 1989; Tilley, 1982). There is a performance trough associated with the circadian nadir occurring around 2:00 p.m. (the "postprandial" dip in performance) and again from 1:00 a.m. to 4:00 a.m. Some cultures acknowledge this performance decrement and accommodate it by providing a designated time for resting, or "siesta", in the early afternoon. Similarly, it is not surprising that many accidents occur in the early morning hours when circadian rhythms are at their nadir, the lowest point of the cycle (e.g., some well-known disasters and the time they occurred include: Chernobyl, 1:23 a.m.; Bhopal, 12:40 a.m.; and Three Mile Island, 4:00 a.m.).

In addition to the substantial differences in performance due strictly to normal circadian variation, fatigue due to sleep deprivation can also be a major source of variance in human performance. Most adult humans require an average of 8 hours of sleep per day. When this requirement is not met, performance can suffer in a most dramatic way. This human performance decrement has been modeled very effectively in computer models such as the SAFTE model (O'Donnell, et al., 1999) [implemented in the Fatique Avoidance Scheduling tool (FAST) computer program, Eddy and Hursh, 2001; Hursh et al., in press] that has been adopted by the Department of Defense (DoD). Sleep inertia, the lethargic feeling that one experiences when awakening from sleep, is also associated with inferior performance (Naitoh et al., 1993; Balkin and Badia, 1988).

A third source of performance variation can be seen in circadian desynchrony when the normal circadian rhythms of an individual are disrupted (see Example 19.1). As anyone who has experienced jet lag will attest, shifts in time zones result in general feelings of malaise and impairment in cognitive functioning. Modern aircraft, with their greatly extended mission durations, have motivated researchers to question how best to manage work and rest cycles during extended missions. Around-the-clock flight operations have become commonplace, both in the civilian and military workplace (DellaRocco; 1999; Caldwell, 1997). In such cases, even limited exposure to normal photic time cues (daylight-darkness) and normal work/social/sleep schedules (day work/night rest and day wake/night sleep cycles) may hamper an individual's circadian inversion and disrupt their sleep patterns. The literature on shift workers is rife with examples of the diminished performance and health risks associated with night shift and swing-shift work schedules (Hossain and Shapiro, 1999).

When assessing operator state, these predictable fluctuations in human performance attributed to circadian rhythms must be considered. The designer should assure that the system can be operated properly, not only during regular business hours (when operated by rested users), but also in the early morning hours when operated by users who have had very little sleep for the preceding week. Table 19.11 lists candidate measures that are frequently used for monitoring circadian rhythms and fatigue.

Example 19.1 Watch Standing Aboard a U.S. Navy Carrier In times of combat and military crisis, U.S. Navy (USN) aircrew members are frequently required to fly a tremendous number of night missions. Recently, a number of aircraft carriers have instituted a remarkable adjustment in the work shift work schedule of their entire crew. To accommodate the needs of

TABLE 19.11 Circadian Rhythm and Fatigue Measures

Acronym	Name	Recording Method	Where Conducted?	Expense	Ease of use
Actigraph	Activity levels	Accelerometer worn on wrist	Field/lab	$$	*
Temp	Temperature: Oral, axillary, aural or core	Thermometers, digital or analog	Field/lab	$	*
Melatonin	Hormone melatonin concentrations	Salivary or plasma level of melatonin	Lab (hard for field)	$$$	†
Ratings	Subjective ratings of fatigue	Subjective rating scales (e.g., Stanford Sleepiness Scale, Epworth Sleepiness Scale, POMS)	Field	Minimal	‡

$ = *Inexpensive*
$$ = *Somewhat expensive*
$$$ = *Expensive*
* = *Minimal training required*
† = *Specialized training required*
‡ = *Highly specialized technical training required*

the flight crews, the entire ship's company has shifted its working hours to a night schedule, which can have unexpected ramifications.

Anyone who has crossed several time zones has experienced jet lag and will recognize the difficulty involved when trying to invert the human circadian rhythm. The schedule inversion implemented by these USN aircraft carriers poses a unique question: Can an entire ship's company be successful in inverting individual circadian rhythms in the presence of normal light or photic cues? How do we assess how much rest an individual is getting and how do we determine if they are "fit for duty?"

A proper appreciation of performance decrements seen in individuals whose circadian rhythms are desynchronized serves as a reminder of the importance of adequate rest for all crew members. Watch-standing schedules specifically designed to safeguard against fatigue and promote sleep hygiene are vital. In the near future, field trials of "fitness for duty" batteries, incorporating physiological and performance tests, will determine whether such batteries will be beneficial to commanders and supervisors.

19.3.3 Psychological and Physiological Stress

Stress is defined as a process by which we receive information and then respond to an event, either real or imagined. Stressors can be both positive and negative. Stressors can have strong motivating or empowering properties, although stressors can also have detrimental effects on our psychological and physical health. Long-term severe stress can lead to a host of medical problems, and severe stress can even contribute to (if not cause) death (Lazarus and Folkman, 1984).

All living organisms respond to stress. The term *stress* (or *stressor*) is used in a variety of ways and can impact an organism individually or in combination. Stress can be induced by *physical or environmental* conditions (e.g., heat, cold, noise, illumination, motion, etc.). It may also be caused by *psychological* pressures (e.g., anxiety, anger/hostility, the "fight or flight" syndrome, threat perception, etc.), and it is also associated with *physiological* factors (e.g., sleep loss, fatigue, mental or physical workload, etc., Wickens, 1996).

The *stress response* system has been eloquently operationalized by Seyle (1937, 1975) using his general adaptation syndrome (GAS), which is divided into three distinct phases: (1) the alarm reaction (mobilize resources), (2) the resistance stage (cope with the stressor), and (3) exhaustion (reserves of energy depleted). In response to chronic stress, these reactions can lead to physical ailments such as hypertension, heart disease, stroke, ulcers, and even death. Seyle's pioneering work on the effects of stress on organisms, and the publication of his "stressful life events scale," represented an attempt to quantify a wide range of typical stressors, both positive and negative.

The "fight or flight" is the characteristic reaction of organisms when exposed to an emergency or to a life-threatening situation (Cannon, 1994). This response offers obvious survival advantages for an organism. When confronted with a life-threatening event, we will instinctively respond by (a) fighting to protect ourselves, or if fighting is not an option, we will (b) remove ourselves from the vicinity by fleeing. But over the millennia, humans have had to face fewer and fewer truly life-threatening or emergency events in daily living. Unfortunately, our anatomy and physiology have not adapted to this less threatening lifestyle. We still respond to life-threatening events, but we also respond to stressors with this same response. This hard-wired fight or flight reaction is at the center of most stress-induced physiological responses and is a causal factor in many physical changes. The following (partial) list of responses is well known:

- Increase in sympathetic nervous activity
- Increase in blood pressure
- Rapid heart rate
- Release of red blood cells/blood coagulant
- Increase in epinephrine
- Surge of adrenaline
- Change in acid/alkaline blood balance
- Redistribution of blood supply (from viscera and skin to brain and muscles)

There is also a wide range of psychological emotions associated with the fight or flight response, and most of these center on thoughts related to escape and the availability of means to protect oneself. During periods of very high stress, such as in combat, individuals faced with life-threatening situations often report a "narrowing" of perception or attention, a clarity of thought processes, and an ability to "hyper focus." Alternately, some soldiers under fire report thought patterns that are so jumbled and disordered that clear thought and action is almost impossible. Different people can (and often will) respond differently to the same stressor (Hancock and Desmond, 2001).

While excessive stress has the potential to cause physical and psychological harm, the opposite extreme—too little or nonexistent levels of stress—is also not good. A moderate amount of stress can be a good motivator, increasing the arousal level of the individual. The level of arousal plays an important role in motivation and task-oriented behaviors. This inverted U-shaped curve describes the effects of stress on the organism and is typically referred to as the *Yerkes–Dodson law.* (For a review of Yerkes–Dodson law, see Teigen, 1994.) At the left end of the inverted U there is so little stress that there is no motivation, while at the right-hand side of the inverted U, too much stress exists. The optimal amount of stress lies somewhere in between, and varies greatly by individual, as well as by the importance of a task, the time allowed for the task, and a host of other variables.

The ability to assess the impact of stressors as a function of their physiological and cognitive impacts on an individual is an important factor for a systems design engineer to consider (Hockey, 1983). Something as simple as requiring an individual to work in an intensely stressful environment for only a limited and prescribed period of time may prove to have extremely beneficial effects on long-term employee health and cognitive functioning. This "exposure-based" approach of allowing workers to work for a limited time in excessively stressful environments is used in many high-stress occupations, the best-known example being air traffic controllers (Stokes and Kite, 1994).

Environmental Stressors Stress takes many forms, including a class of stressors termed *environmental stressors* (Banderet et al., 1987; Kanki, 1996). Environmental stressors are those factors in our physical environment that can have a negative effect on our ability to function physically or cognitively. These factors exist around us, in one form or another, all the time. Such factors include:

- Excessive heat (and/or) excessive cold
- Climate (humidity)
- Illumination (both quality and intensity)
- Motion (on a vehicle; vibration from machinery; g forces)

- Noise (excessive noise requires hearing protection)
- Quality of air (ventilation odors; particulate matter requires breathing protection; high altitude requires supplemental oxygen; underwater diving requires pressurized air)
- Air pressure (very little at high altitudes)
- Water pressure (very high pressure while diving underwater)
- Social (working alone vs. part of a team or group)

When one or more of these variables leaves the normal range, we begin to notice and become aware of the way they affect our ability to function (Griffin, 1997).

Background Stressors Finally, there is the concept of daily hassles. Daily hassles are those everyday, relatively minor "background stressors" that have a cumulative and annoying effect on us (Hahn and Smith, 1999). This additive effect can lead to physiological and psychological effects that parallel the effects of regular stressors described above. For example, imagine if a system has small warning lights and audible alarms. The warning lights are not to signify emergency conditions, but rather to alert an operator that attention is needed on some time-critical process or function. As such, the warning lights are designed to help allow the operator to attend to systems other than the one on which he/she may be concentrating. However, if these small alarms, not particularly annoying by themselves, start lighting up and sounding every few minutes, the operator must reset the equipment, silencing the warnings, and then continue normal activities. If these false alarms continue, the operator is likely to find a way to permanently silence them. The cumulative effects of such seemingly small hassles build until the operator experiences significant stress. Systems engineers and designers should be reminded that if such systems are designed to continuously alert an operator, the cumulative effects of those warnings can contribute to the stress they were designed to ameliorate.

19.3.4 Situation Awareness

Situation awareness (SA) can be described as an awareness or knowledge of what is going on around you. The definition of SA also takes into account the accuracy of the information, as well as how much the individual believes the information to be accurate. There is a tremendous amount of information available in the world but not all of that information is available to or perceived by the human operator. Figure 19.3 illustrates how information about the state of the world is sequentially filtered to yield the most basic level of human operator SA (Pew, 2000).

The top level of the figure is "ground truth" which consists of each piece of information and every data point that is available about the world. Sensed Truth or Potential SA is the next level in the diagram and includes all information that is sensed, whether directly or indirectly. Of course, as our sensor capabilities improve, we know more and more about the state of the world around us but it can be argued that we will never know everything about the world. The difference between the first two levels represents the inability or limitations of our sensor capability.

Operator SA is at the bottom level of this cone of awareness and is a subset of sensed truth or potential SA. All information that has been sensed or detected is available at this level for the human operator. Of course, due to limitations on human information

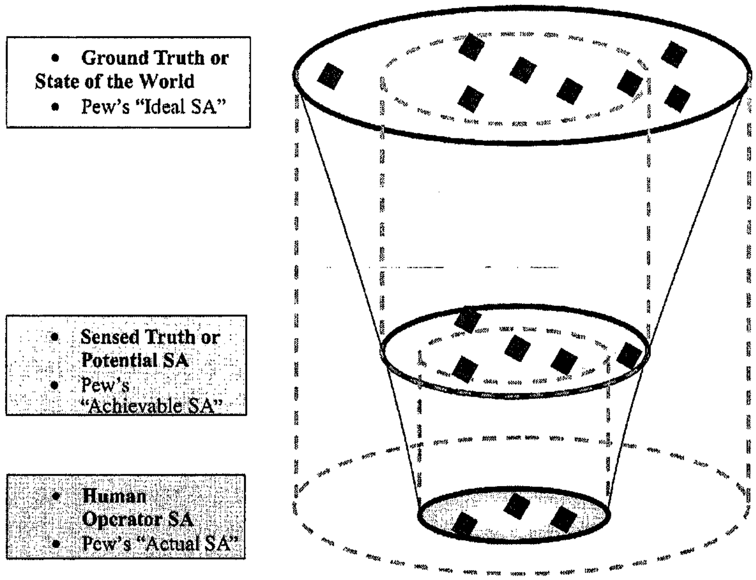

Figure 19.3 Depiction of situation awareness.

processing, the human operator will not perceive everything detected by the sensors. Endsley and Garland (2000) describe SA as a three-tiered process of perception, comprehension and projection. These three stages are described as Levels 1, 2 and 3 SA. In Figure 19.3 the lower level represents perception or Level 1 SA.

To acquire and maintain SA requires an awareness of what is going on around you, followed by the ability to make judgments concerning things to which you should attend. This process is a type of "cognitive filter," which allows an individual to make decisions on the relative importance of environmental features. Depending on the situation and context, we may use all of our senses in assessing our environment, while at other times we may use only a subset of the available sensory modalities. We may use one sensory modality to such an extent that we ignore other senses. For example, a pilot has to learn to maintain SA, not only using the eyes and ears, but by attending both physically and cognitively to important information, while concurrently ignoring or "filtering" irrelevant information. SA is more than just keeping a mental picture: It is a dynamic process whereby an individual maintains environmental awareness and is also aware of what to ignore in the environment (Hartman and Secrist, 1991; Endsley, 1995; Endsley and Garland, 2000).

Aids to Enhance Situation Awareness Situation awareness is an internal state that is acquired and maintained by the individual and therefore differs from many other factors that a systems design engineer considers. Individuals vary considerably in their ability to acquire and maintain SA. Various types of equipment have been used in attempting to "design in" aids to SA for the system operator. Such aids help an individual acquire and maintain SA, while at the same time enhancing their ability to attend to other functions or problems.

One well-known and very successful example is use of the HUD ("Head Up Display") in a cockpit. This system helps a pilot maintain SA by allowing an awareness of the world

outside while simultaneously maintaining an awareness of vital flight parameters. From this perspective, a HUD can be conceived as more than simply a means to view flight parameters, but rather as a SA-enhancement device (Will, 2000; Leger et al., 1999). However, HUDs have also been found to significantly *decrease* SA when an individual's attention is overly focused on the information presented on the HUD, thus diverting attention away from other critical (often dangerous) environmental cues (Weiner, 1989, 1990, 1993).

Quantifying Situation Awareness While attempts to quantify SA have been met with mixed results, a critical consideration is how to accurately measure an individual's SA (Vidulich, Stratton, and Wilson, 1994). Pritchett and Hansman (2000) divide SA measures into 3 categories: knowledge-based, verbalization measures and performance-based. The strengths and limitations of the various measures are succinctly described in tabular form in their chapter. For more in-depth information on these measures, the reader is referred to Endsley and Garland (2000) and Gawron (2000).

Enhancing Situation Awareness The workplace configuration and the cognitive task demands on the human should be taken into consideration when designing a SA enhancement system. There does not appear to be "too much" SA. However, the danger lies in assuming that "more is better." Endsley offers a list of 50 principles for enhancing SA in systems design. A design should always take into account the *desirability* and *need* by a person to enhance or modify the level of SA. It is important to determine the optimal level (and type) of information delivery that will *enhance* SA, while not inadvertently obscuring or clouding existing SA. Poorly designed equipment or interfaces, the delivery of too much unimportant information, and poorly presented information can hinder the development and maintenance of SA. An experienced operator will have learned to attend to various cues regarding the state of the environment and equipment, some consciously and some at the level of the sub-conscious and unconscious level. That "funny feeling" that individuals often use to describe their sense of an impending equipment failure can be explained by the various cues that are constantly being processed by the user.

The Temporal Nature of Situation Awareness One variable that significantly impacts SA is time. SA is time-sensitive. The salience or "newness" of SA information is inexorably tied to the length of time that has elapsed since it was last refreshed and the rate of change of relevant information in the task at hand. Periodic updates are essential to maintaining SA. The rate of updates to SA information varies considerably, and is typically a function of task requirements and the ability of an individual to receive periodic information updates. These updates may need to occur frequently (e.g., demanding air traffic control tasks), or more methodically (e.g., monitoring of aircraft instruments on autopilot at cruising altitude). One important factor that greatly influences the time it takes an operator to acquire and maintain SA is the level of familiarity the operator has with a particular task or situation. We are able to respond most rapidly to situations with which we have the most familiarity (i.e., over-learned behaviors). Our ability to respond to new situations is heavily impacted by our knowledge of previous, similar situations. Additionally, there is a learning curve that occurs while attempting to master a new system. Before an individual will acquire high levels of SA, they must have achieved mastery of the new system.

New Frontiers in Situation Awareness Recently, the concept of SA has been extended beyond previous definitions. One new technological area that involves SA, but relies entirely on synthetic sources of information, is the emerging field of "remote" SA. This involves the ability of an operator to acquire and maintain SA when operating an unmanned aerial vehicle (UAV) via remote control. This technology, also called "tele-robotics," relies on remote sensors to provide the information necessary for the operator of the UAV to acquire and maintain SA. As with any new technology, many questions remain unanswered. Can a machine be equipped with an appropriate set of sensory devices that transmit vital "real time" SA information back to the operator? And how well does the operator receive such information, selectively attend to it, and form a reasonable mental model of the situation? Such "cutting edge" questions are germane to the discussion of the role of human systems integration, cognitive task demands, and workplace configuration in the situation awareness of the "human-in-the-loop."

19.4 HUMAN SYSTEMS INTERFACES

This section addresses the critical juncture between the human and the machine and gives guidance for systems designers who are striving to optimize total system performance while making the most effective use of the human. These guidelines are divided into four sections:

- Workspace design and anthropometric considerations
- HSI considerations for the design of displays
- Task allocation: man versus machine
- Social issues and team performance

19.4.1 Workspace Design and Anthropometric Considerations

From a human systems design perspective, it is important to focus the design on the population of individuals who will be the end users. The importance of designing with the user in mind is no more readily apparent than in work space design issues. A worker in a poorly designed work environment will be less productive, more error prone, more injury prone, and eventually may no longer be able to work due to repetitive strain injuries (RSI). Optimal work space design increases worker productivity, enhances safety, contributes to a reduction in worker errors, reduces work-related injuries, and lowers personnel turnover.

Several criteria typify developing new work space environments. These include *the use of anthropometric data.* These data require more than a simple "look-up table" approach. Anthropometric data may be easily misinterpreted or misapplied. If used inappropriately or carelessly, or if interpreted incorrectly, these data may do more harm than good. The same thoughtful, methodical, and comprehensive approach one would use in the design and selection of material for a project should be applied when using anthropometric data.

Thoughtful Application of Anthropometric Data Determining which data table to use and applying those data judiciously is not enough. A systems designer should keep in mind several key points before using such data. These points reflect the system under

design and the potential user population. Similarly, if data for a particular design dimension do not exist, the same care should be taken in acquiring the necessary data.

Know the Population of Users under Consideration Who will be using the system? What characteristics do they posses? What are the human user requirements (physical, cognitive, skill level, etc.)? What kind of physical demands will be placed on the user in the work space? What will the operating environment be like?

Determine Essential Body Dimensions and Which Dimensions Are Most Important for Design Similarly, which dimensions are practical, given economic, weight, size, durability, and maintainability considerations? When referring to anthropometric tables/charts, always use recent data (individuals and general populations *do* change over time). Do not extrapolate or attempt to correlate dimensions from existing data unless you are aware of how doing so may skew the data. There is always the potential for complex and unforeseen interactions between measurements.

Determine Percentage of Population Accommodated This consideration may vary depending on the use of the system. Consumer products require much wider population variances than military systems, for instance. While it is obviously impractical to fit a design or process to 100 percent of the population, it is important to know in the conceptual design phase who comprises the population of users and what percentage of them you intend to accommodate.

Design to the Portion of the Population That Has Been Selected for Accommodation Use the average of that population as a midpoint and develop a design that is adjustable or modifiable for the variance of that population. Again, for commercial systems, the populations have larger variances than military populations. Make necessary adjustments using anthropometric tables for reach and clearance envelopes, seat adjustment envelopes (transportation equipment), etc. Like all design trade-offs, the more flexible the design becomes in one area, the more likely certain constraints will appear in other areas of the design.

Use prototyping, mockup, simulation, and computer-aided design tools in the concept exploration phases to determine if human user requirements are met. Early design verification for user fit will save time and money in later engineering phases. (Gawron et al., 2002). Other appropriate considerations in the design of a system and its user environment include:

Determine the Controls and Tools Necessary to Perform System Tasks Primary and secondary controls and tools must be inside the reach envelope for the population selected. Tools, controls, or parts that the worker must reach and use most often should be placed within the primary reach envelope, while tools, controls, and parts used less frequently should be placed progressively further away (in secondary or tertiary reach envelopes).

Determine the Physical Characteristics and Clearances (e.g., leg, head, arm, etc.) for Users of System Comfortable seating, adequate legroom and headroom, sufficiently wide passageways to/from the work location should all be planned. Many populations include special-needs members such as users with limited mobility, sensory limitations, and/or pregnancy.

Physical characteristics of the work surface must take into consideration such factors as height, depth, clearances, and inclination of the work surface. Overhead or side tool storage must be placed to allow access with minimal disruption to productivity.

Maintenance of the system requires accessibility to maintainers. Designing for maintenance requires that the system be usable and accessible to both its operator and maintainer (see Example 19.2).

Example 19.2 Engine Room Habitability The engine room crew of a nuclear aircraft carrier has to contend with issues involving the "habitability" domain—that is, those issues associated with living, sleeping, and eating within the confines of the systems the crew is operating and maintaining.

The design engineer in this context is commonly referred to as a marine architect, namely, one who designs ships. A major challenge for the marine architect charged with designing a turbine engine compartment deep within a modern aircraft carrier would be habitability. Because space is at a premium, it is no small task to design a space large enough to hold the engines and ancillary equipment, but to also ensure that the crew members who will work within this environment are able to safely and effectively perform their assigned tasks.

Another issue is the high stress levels likely to be a factor for the engine room crew. The work environment is inherently stressful (high heat, extremely loud, close quarters; physically uncomfortable work positions). The unpredictable nature of equipment malfunction and the requisite necessity to work at odd hours or "on call" to operate and/or repair equipment can add to this problem. Inability to "get away" from work—most engine room crews' sleep and eat in relatively close proximity to their duty station—combined with working very long hours can induce high levels of stress and fatigue. Due to the nature of the work location (far below decks), individuals may not see daylight for a week or more. Crewmembers also must maintain a high level of SA due to the dangerous environment.

19.4.2 HSI Considerations for Design of Displays

Many, if not all, modern systems involve the display of information. Complex presentation of information has been designed into modern weapons systems, power generation plants, and desktop workstations. The goal of any display is to optimize the performance of the person using the system while allowing for a reduction in errors (Woodson and Conover, 1966).

Visual Display of Information Visual displays should be designed so that users are able to easily and quickly ascertain the state of the system at a glance. While good displays facilitate accurate transfer of information from system to the human, poor displays may contribute to accidents and errors. Poorly designed displays may make it difficult for the user to quickly and accurately detect a problem or determine and implement a solution. Designing a usable visual display does not require extensive knowledge of vision theory and the supporting brain and cognitive functions. There are principles that can be applied by the design engineer in planning and developing a system that people can use successfully. Table 19.12 lists many of the factors that should be considered when designing a system that requires the use of visual information.

Ambient lighting must be adequate to allow the person to see the task at hand. For some jobs, supplemental *task lighting* must be added so people can see what they are doing. For example, kitchen designers provide an overhead (ambient) fixture, but also include task lighting over the stove, in the oven, and over work surfaces. Detailed work may require

TABLE 19.12 Visual Characteristics Useful for Human Systems Design Consideration

Visual primacy: As the dominant sensory system for humans, vision is used for orientation, intake of information, and verification of other senses. In the absence of visual input, other sensory systems become more important.

Light levels: Ambient light levels have a profound effect on visual functioning. Light levels that are too low inhibit detection and color vision while light levels that are too bright, e.g., direct glare, can be equally disruptive to vision.

Edge detection: The visual system of humans has built-in "edge detectors" that allow for immediate recognition and detection of edges.

Motion detection: Built-in motion detectors allow for immediate and automatic recognition of movement and are obviously important in many technologies.

Pattern recognition: The human visual system has an excellent ability for pattern recognition, which is particularly useful in monitoring tasks or for off-center vision. It is automatic and allows for the rapid integration of dissimilar visual elements into a cohesive whole. For example, on an aircraft display, symbology is used to facilitate rapid recognition of visual targets.

Coding: Visual design of information can be coded to give more information in less space. The addition of color, shape, or grouping to indicate another dimension is an excellent practice that tells the user more in less space.

Gestalt: Visual information should be grouped to ensure that similar items are processed as a unit. Control panels that have related controls "boxed" together using linear demarcation facilitate human performance and allow the operator to quickly detect when one gauge is out of range.

more light. There should also be adequate contrast between the area of attention and the background. Kroemer and Grandjean (1997) provide excellent guidance for the placement of light for visual work.

Because people tend to identify things that are placed close together as a group, gauges, dials, or other items that are closely related should be located in close proximity to one another (Chapanis et al., 1963). Displays should be grouped according to use. For instance, in an aircraft, all the displays having to do with engine health should be located together. The displays should also be arranged to allow "quick looks." Many aircraft displays are installed so that the indicators for normal operations are in the same position (e.g., 12 o'clock) for all the displays in a group. *Display consistency* allows the operator to quickly glance at a display to determine whether the system is functioning properly. Displays should be directly linked with their controls by putting control actuators (knobs, dials, etc.) on or close to the display. There should be little or no delay or lag in the display/control interface. Displays need to be properly lighted to ensure readability in all lighting conditions that may be encountered. In an aircraft, the system should accommodate for light levels ranging from night light, low light, low sun angle light, to bright sunlight. There should also be good contrast and readability in all lighting levels. Human Engineering Design Criteria for Military Systems, Equipment and Facilities (MIL-STD-1472) is a useful resource for basic design. The MIL-STD 1472 (currently in version F) contains some basic considerations that apply to all systems in which visual information is presented.

There are a number of other important visual principles related to presentation of information (Tufte, 1983, 1990). Some important design considerations include redun-

dancy, alarm and caution signals, and display type. *Redundancy* is the presence of information in more than one place and/or in more than one sensory modality. *Color coding* is an example of different modes, while the presence of a digital and analog clock on a display is an example of information in more than one place and in more than one mode. Another consideration is that while many people have good color vision, an inherited deficiency in color vision (color blindness) exists in about 10 percent of the population, primarily males.

Redundancy helps people gather information by presenting data in more than one way. *Alarms and cautions* have a range of urgency and can be presented in multiple ways. For example, alarm or caution information may be presented in red (color coding) or flashing (to catch the user's attention) or coupled with another sensory modality to ensure that the user identifies a problem and initiates a solution. *Display type* includes both the method of information presentation (e.g., digital vs. analog) or means of presentation (e.g., CRT, AMLCD, plasma, etc.). The method of presentation should be carefully considered to ensure that the user receives the information in the most usable way. For instance, while digital speedometers in cars were tried for a short while, it was difficult to control speed because digital speedometers show state information. Speed control requires trend information (e.g., is the vehicle accelerating or decelerating?) As has been shown, vision is a complex but critical information channel whose use should be optimized to ensure peak user performance.

Auditory Display of Information As with vision, since so many modern systems use auditory cues to convey information, this section focuses on general design principles critical for the system designer to know about the auditory characteristics of the human. Table 19.13 lists auditory characteristics that are of primary consideration by systems engineering design teams.

Typically, vision and audition function together. For example, a radio call alerts a pilot to air traffic and the pilot begins a visual search. Auditory information is processed serially while visual information can be processed in a parallel fashion. Auditory signals can range from simple (e.g., warning horns) to complex (e.g., speech). The auditory channel is well suited to the presentation of imperative information, such as warnings or cautions. But for most tasks, audition should supplement visually presented information, rather than being

TABLE 19.13 Auditory Characteristics Useful for Human Systems Design Consideration

Auditory localization: Humans are very good at determining the direction of a sound source, with the exception of sounds generated on the exact centerline, i.e., directly in front or behind the operator.

3D auditory capability: The occurrence of a sound in three-dimensional space allows a user to receive information other than the location of a sound. This feature of the human auditory system can be used to aid a user who is overloaded with visual input.

Pattern recognition: Auditory pattern recognition is very similar to visual pattern recognition. This process occurs automatically and allows for the rapid integration of dissimilar auditory elements into a cohesive whole (e.g., music recognition).

Tones vs. speech: To be effective, alarms need to be audible and distinctive in the operating environment. Alarms do not have to be transmitted verbally as long as their intent is conveyed.

the primary source of information. Auditory displays of information should be limited to short messages or information that requires an immediate response. The auditory display alerts the user to make use of the visual display for more complete and amplifying information. While verbal displays may provide more information, they may also take longer to present the information than if it was presented visually. MIL-STD-1472 provides guidance for the use and design of verbal displays.

People with normal hearing exhibit temporal proximity, that is, tones close together in time are perceived to be together. People also exhibit auditory similarity based on the pitch of the sounds (i.e., sounds that have similar pitch are perceived as a group). Humans have the ability to localize sounds in three dimensions [i.e., they can determine the direction of the source of a sound (Proctor and Van Zandt, 1994)]. Three-dimensional displays provide location information. The localization of the signal alerts the user to the position of a threat or other sound and is very different from the information conveyed visually.

Haptic Sensory Display of Information Virtual environments have increasingly relied on the insertion of haptic cues to enhance the user's sense of immersion in the virtual environment. In particular, one journal, *Presence*, has a wealth of information on haptics and their use in virtual environments. Staying abreast with developments in this rapidly changing field can be challenging but rewarding for those wanting to include senses other than just vision and audition in virtual environments. In aviation, user presentation of information using the touch sensory modality has focused on the presentation of attitude, proximity, and spatial mapping of information [e.g., U.S. Navy research on a vibro-tactile suit to display aircraft attitude information to the pilot (Rupert et al., 1994; Rupert, 2000)]. The touch senses do not transmit highly specific information as occurs more commonly in the visual and auditory senses. This characteristic does not in any way discount the utility of the touch senses for a more general display of information, improving SA, or for redirecting operator attention. Table 19.14 illustrates the touch characteristics that are important for consideration in HSI applications.

TABLE 19.14 Touch Characteristics Useful for Human Systems Design Consideration

Proprioception: An awareness of the position of our body joints relative to each other and to our body. This includes awareness of the position of the body in space and with respect to objects in the environment.
Sensitivity variability: Sensors are more closely spaced in some areas of the skin than in other areas (e.g., the skin on the tips of the fingers has many more receptors than does the skin on the back.). Thus, if the operator is required to detect small patterns, it would be better to use the tips of the fingers than the skin on the back. One example of this is the use of the fingers to read Braille letters in visually impaired individuals.
Haptic: When touching an object, we respond to the shape and feel of a manipulated object. Shape coding of controls uses the haptic sense to impart more information for operation of the control without visual input (blind mapping). Vibro-tactal display devices capitalize on haptic sense. Another haptic design consideration is control actuation feedback.
Kinesthetic: Our ability to sense the relative motion and speed of movement of our limbs. There are no practical design considerations for kinesthesia at this time.

19.4.3 Task Allocation—Humans versus Machines

Any comprehensive discussion of the human component of a total system should include a section comparing human versus machine or nonhuman abilities, highlighting the relative merits of the two subsystems. Task analysis is a method used to determine which part of a system should perform different types of work.[4] It ensures that each task is assigned to a specific part of the system being designed and helps to illustrate what characteristics are most appropriate for the successful completion of a task. For example, if a requirement-driven task is "monitoring a fuel level," the task of monitoring the fuel level may be levied on a computer subsystem, while the task of "monitoring the monitoring of the fuel level" could be assigned to the mission commander, a human subsystem. Task analysis can also be used to model the distribution of tasks across a system and/or team and determine the effect of that distribution. Task allocation can be reiterated until optimal performance is achieved.

There are a number of task types that are better left to people or the human subsystem, while other tasks are better left to machine subsystems (Parasuraman, 2000; Parasuraman et al., 1996; Parasuraman and Riley, 1997). Table 19.15 lists tasks that are performed better by humans and tasks that are performed better by machines.

19.4.4 Social Issues and Team Performance

While working with other people is generally beneficial, desirable, and often necessary, it is also not without its problems. The vast majority of us are intimately tied to our social environment. We are heavily influenced by social factors, and this social environment exists completely within our physical environment. We think and work differently as a function of our social environment. Yet we have become so accustomed to living and working within this social climate, that we are rarely conscious of it. A pervasive theme running throughout this section is to make the reader aware of the influence of factors that are easily overlooked—in this case, the social factor.

One very important factor that is often ignored in the planning, design, and operation of many complex systems is the social nature of the human user. Social interactions are a very important part of our lives, and because these interactions so strongly influence our behavior, we need to be aware of the processes and social dynamics that influence the operator/user. Both the physical workplace configuration and the cognitive task demands placed on the human operator/user should be considered within this social milieu.

Social Interactions It is important to consider the social processes that occur when an individual in a system interacts with other people. Social interactions refer to the subtle yet pervasive verbal and nonverbal interactive styles all humans exhibit. These interactions are important whenever two or more people are required to function as a team, and become even more important when that team is responsible for controlling highly sophisticated, technologically intense, and potentially dangerous equipment (e.g., nuclear power plant, chemical factory or oil refinery, air traffic control operations, etc.).

Social Comparison People assess each other constantly. From a human factors perspective, this social comparison can influence our actions in ways that defy the attempts of engineers to accommodate them in the system design. Pilots or others in high-risk, high-

TABLE 19.15 Task Allocation to Appropriate Subsystem

Example of Tasks Performed Better by Humans	Example of Tasks Performed Better by Machines
Detection of certain forms of very low energy levels	Monitoring of humans and machines
Sensitivity to an extremely wide variety of stimuli	Performing routine, repetitive, or very precise operations
Perceiving patterns and making generalizations about them	Responding very quickly to control signals
Detecting signals in high noise levels	Exerting great force, smoothly and with precision
Ability to profit from experience and alter course of action	Insensitivity to extraneous factors
Ability to react to unexpected low-probability events	Ability to process many different things simultaneously
Applying originality in solving problems	Deductive processes
Ability for fine manipulation, especially where misalignment appears unexpectedly	Ability to repeat operations very rapidly, continuously, and precisely the same way over a long period of time
Ability to perform even when overloaded	Operating in environments that are hostile or dangerous to humans or are beyond human tolerance
Ambiguity resolution	Continuous collection of data to support decision making
Ability to reason inductively	Deductive reasoning
Tasks requiring high motivation or involving strong emotions	Consistent reasoning across all cases
Remembering exceptional cases	Remembering all cases (and the probability of each)
Following hunches/flexibility	Consistent application of rules to situations or cases

tech occupations may perform their job poorly or in an unsafe manner in attempting to gain the approval (or admiration) of those around them, or perhaps to flaunt their "mastery" of a complex skill.

Diffusion of Responsibility The attribution of responsibility can be ascribed to an individual's deference to the "person in charge." Unfortunately, this communication is often made in non-verbal ways, which can leave the senior individual under the assumption that "...if I do something wrong or unsafe, he/she (e.g., the junior individual) will tell me about it," when in fact the junior individual may remain quiet out of respect (or fear) of the senior individual. The subordinate may also feel it is "not their place" to alert their superior to a potentially dangerous situation. Such unstated assumptions can have disastrous consequences (Evans, 2000).

Computers provide assistance to the operator in most modern complex systems, but as long as humans are an integral part of such complex systems, the potential for human error will always be present (Parasuraman et al., 1996; Wiegmann and Shappell, 2001). Failure to take into account the personality, social interaction style, and the ability of individuals to

effectively communicate and work together *as a team* during critical aspects of any complex operation is to invite disaster (see Examples 19.3 and 19.4).

Example 19.3 Crew (or Cockpit) Resource Management To appreciate why flight crew training and coordination is so important, one can look at safety statistics that demonstrate that approximately 70 per cent of all major airplane accidents were caused by aircrew mistakes (O'Hare and Roscoe, 1990). Crew resource management (CRM) was developed to mitigate some of the more dangerous social aspects of human performance in a complex system, specifically to improve performance in multiplace aircraft (Weiner et al., 1993). Performance of the multiplace aircraft system is dependent on the crew working *together* to detect and solve problems as they occur in flight operations. Crew coordination is combined with other decision and performance aids such as checklists and instrument configuration changes. The CRM approach is often associated with checklist design but goes well beyond the checklist. Crew coordination focuses on determining a process for performance, and following that process, to ensure safe performance and successful mission completion (Brown et al., 1991).

Example 19.4 Automation and Fight Emergencies One of the issues in modern aircraft flight decks is the misallocation of crew and equipment resources. The current generation of computer-controlled "fly-by-wire" aircraft has sophisticated instrumentation and onboard computers capable of flying the entire route from take-off to landing. While this reduces the workload on the crew, the design of these automated systems are not based on the performance strengths and limitations of the system subcomponents (the computer and the human operator). Therefore, although workload is reduced in regular operations, the operators are forced to perform monitoring tasks, which humans perform poorly. In emergencies, the operators, who have been tasked to monitor the system, may not have the information needed to resolve the emergency and are required to "catch up" to the rest of the system when time is short.

19.5 CASE STUDY

For all systems that include the human as an operator and user, there are certain considerations that are universal. Perhaps most obvious is the physical consideration that involves fitting the human *into the system*, whether it is in a crew station, control room, or cockpit. Sensory, perceptual, and cognitive considerations are also required for all systems: The operator must have the ability to sense and process information from the system to make decisions about how to control it. The following case study illustrates the importance of human consideration in HSI. Although based on a real military system and tasks, the case study is hypothetical and not meant to be used as guidelines for actual systems.

Unmanned Aerial Vehicle [UAV(x)] System This case study is for a hypothetical UAV system design that we will term UAV(x). The DoD has actually invested heavily in both the technology and capabilities of UAVs. As shown in the war in Afghanistan, UAVs can function in a wide variety of roles *without endangering the life of the human operating the system* (i.e., a pilot). Other benefits of the UAV besides pilot safety are weight savings and a larger payload for sensors. The UAV itself is only one component of a very complex system. It requires many of the same things that a piloted aircraft requires, including a runway, a hanger for maintenance, the ability of maintenance personnel to readily access

major components for repair/replacement, etc. Unlike a piloted aircraft, however, it also requires a "cockpit" apart from the UAV itself, typically at a remote site to allow the "pilot" (or operator) to "fly" the aircraft from a distant location.

Table 19.16 provides an engineering description of the UAV(x), which includes an example of the operational and hardware requirements that the engineering community might provide for such a system. Usually the engineering community will also provide the human interface requirements in very general language. As shown in Table 19.16, the "pilot" is expected to "fly" the UAV for the duration of its flight, and should have flight experience and good SA. The HSI program manager should identify special issues to be included early in the engineering design process (see part IV of Table 19.16).

The UAV operator selection is a critical HSI issue. How do we select and train an operator for the UAV system? What human characteristics and capabilities are required to operate a UAV? How long a shift can an operator work without impairment in performance? Are there standards that could be developed and applied to operators of UAVs? Who will make the best UAV operators?—Experienced pilots/aviators *or* specially trained operators with extensive training in UAV operations?

TABLE 19.16 UAV(x) Operational and HSI Description

I. Operational Requirements: Ability to taxi, take off, fly, and land like a manned, fixed wing aircraft; ability to fly to specific coordinates and loiter (either manually or by ground-based operator direction) or via autopilot; good fuel efficiency to remain on station for extended periods; ability to respond to operator commands and send operational and avionics data back to ground operator; speed of vehicle not a primary design consideration; weight of payload and endurance.

II. Hardware Requirements: Fuselage with wings; tail assembly; propulsion system (jet or propeller); avionics and communications bay; fuel tanks; landing gear (fixed or retractable); hydraulic system (if needed); wiring and piping; payload bay(s): video camera(s), still (digital) camera, IR sensor, electronic warfare (EW) offensive capacity, offensive missile capacity, defensive systems (EW; chaff, IR flares; etc.); IFF and/or transponder for identification in combat/controlled airspace; GPS receiver to aid in localization; payload bay designed to optimize quick equipment change with minimal down time; low noise level of vehicle designed to avoid detection; use of lightweight material imperative; shape of fuselage incorporates "Stealth" technology to reduce radar return.

III. Human Interface Requirements: Control station (flight deck) must allow for full flight control of the UAV from takeoff, to mission control, to landing; control station must have the ability to transmit data to the UAV and receive data from the UAV in real time; video image(s) must be received and displayed as clearly as possible; flight controls must be suitable for wide range of operations and should be similar (where possible) to flight controls on regular aircraft. The individual(s) who operate or "fly" the UAV remotely will likely have some flight experience and should have good hand–eye coordination, good situation awareness, and good mechanical/electronics abilities.

IV. Special HSI Issues

1. Skill requirements for UAV operators
2. Ability to "fly" vehicle from remote location
3. Remote station multitask displays design
4. Operator fatigue for long period flights
5. Vehicle recovery and repair time

The military has considerable experience in selecting, classifying, and training pilots and aviators over the last century. Pilots and aviators enter flight training schools and are quickly advanced into flying specialized military aircraft based on their skills and performance in flight schools—or else they are moved into nonflying activities. But regular flight school revolves around one major fact—the pilot is actually in the aircraft he or she is flying. But with a UAV, the opposite is true, the pilot/operator flies the aircraft remotely via sensors and avionics information relayed via data links from the "flight deck" to/from the UAV. Although there are obvious similarities, the operation of a UAV is considerably different from the operation of a regular manned aircraft. Examples of operational issues with the UAV, which are not issues with manned aircraft, include the ability to maintain SA, ability to respond to vestibular cues (aircraft motion), ability to view the world in 3D and ability to respond to events quickly without time delay in the data link.

Because UAVs are capable of staying airborne for extremely long periods of time (Global Hawk can remain airborne for over 4 days), issues of operator fatigue, crew rest, appropriate handoff between crews, and the decay in performance seen over time with vigilance tasks are critical considerations for this system. Monitoring the fluctuations of operator efficiency, as evidenced by operator states, will ensure optimal system performance.

A special document might be prepared for any new system listing the HSI characteristics and quantification methods of special characteristics. As shown in Table 19.17, critical human characteristics for the UAV(x) include the target audience description (operators and maintainers), human factors design of the remote control station, and special maintenance requirements for the system. For measures of many of these characteristics, the Armed Services Vocational Aptitude Battery (ASVAB) provides the skill categories (CAT I, II, III, IV) (see Chapter 11), and MIL-STD-1472 provides the general standards for human factors engineering of crew stations and maintenance (see Chapter 7).

19.6 SUMMARY AND CONCLUSIONS

As is the case with all natural systems, the complexity of the physical forces and the resulting interaction of the organisms within the systems are vital elements in understanding how systems operate and can be designed for optimal performance. In this chapter, we have pointed out the need to consider the characteristics of the human components within our "man-made" systems engineering ecosystem.

Understanding the strengths and limitations of the human operator and maintainer is imperative to the systems designer. Humans have measurable psychological and physical characteristics; some of these characteristics are traits, innate and relatively unchanging; others are transitory states that may vary according to a range of conditions. The ability to quantify these human parameters provides a tremendous advantage to the systems designer. Design trade-offs made with an understanding of these human characteristics are more likely to result in a superior product with improved systems performance than one where these characteristics are not a priority. Ultimately, understanding the salient human considerations can allow the design engineer to tailor a system to effective and efficient performance, both from a total systems perspective as well as that of the human user.

TABLE 19.17 UAV(x) HSI Characteristics and Quantification Methods

Human Characteristics	Quantification Methods
1. Target audience description	
• Operator skill requirements	
• High aptitude—CAT II	• Military ASVAB scores
• Visual acuity—20/20 correctable	• Snellen eye chart
• High hand–eye coordination	
• Good 3D spatial perception	• FAA—air traffic control tests
• Flight training	
• Operator anthropometric limits	• Body height, leg length, arm length
• Male/female 5th–95th percentile	
• Maintainer skill requirements	• Military ASVAB scores
• Average aptitude—CAT III	
• Avionics qualified	
• Number of personnel	
• Operators—1 per vehicle	
• Maintainers—1 per four vehicles	
2. Remote Control Station	
• Workstation design for one operator; layout lighting, controls, displays, alarms, seating in accordance with MIL-STD-1492.	• MIL-STD-1472
• Multitask displays capable of representing 3D spatial images of aircraft environment in form easily detected and processed by operator.	• NASA/FAA standards
• Ability to quickly acquire and maintain SA using data provided from UAV	• SA measures for distant SA via data link need to be developed.
3. Maintenance	
• Parts removal and repairs to be 80% organizational level.	
• Vehicle maintenance hatches, equipment bays easily accessible; equipment within each bay easily removed/replaced with minimal UAV down time; reconfigurable software must allow for modifications as new hardware is added or removed.	• MIL-STD-1472
• Remote station flight deck and related electronics designed for easy access to all components	

This chapter presents an overview of human characteristics that should be considered within a total systems perspective. It is pointed out that individuals can be defined and characterized using a variety of criteria, including broad categories of "trait" and "state." *Human traits*, or those characteristics of the user that tend to be static and unchanging, are described along with corresponding measurement techniques. *Human states*, or those characteristics that vary based on individual responses to operational and/or environmental conditions are also described. Such states may be complex responses to environmental conditions and/or demands, or they may entail individual reactivity to internal processes. In a section on human–system interfaces we provide some guidelines for bridging crucial junctures between human and machine. Guidelines such as these should

be useful to the systems engineer seeking to optimize system performance through effectively integrating the human into the system design. Finally, a case study on the design and operation of a hypothetical UAV system is used to illustrate some of the HSI lessons learned throughout the chapter.

If the human component of the systems are to perform to their optimum, it is recommended that human factors professionals be on the design team and basic iterative human factors design principles be used in all phases of the systems engineering process, especially during the concept development phase. To obtain HSI support from certified human factors professionals, the Human Factors and Ergonomics Society (HFES), the Board of Certification of Professional Ergonomists (BCPE), and the International Ergonomics Association (IEA) are useful resources. The web sites for these organizations have been listed at the end of the reference section.

NOTES

1. Although the domains for manpower, personnel, and training (MPT) are important to a complete description of the human component, MPT descriptions and issues are not covered in this chapter. Chapters 11 and 12 cover the MPT characteristics important for system engineering and management issues.
2. Table 19, page 103, of Gawron (2000) lists these measures, along with estimates of reliability, task time, and ease of scoring.
3. Personal communication, John Rohrbaugh, June 2002.
4. See Chapters 10, 11, 13, and 20 for details on task analysis.

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